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Performance of optimized sound field control techniques in simulated and real acoustic environments

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Outline

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- Introduction
- Sound field control techniques
- Motivation for numerical optimisation
- Optimisation procedure and cost function
- Experiments – anechoic simulations
- Experiments – automotive measurements
- Conclusions

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Introduction

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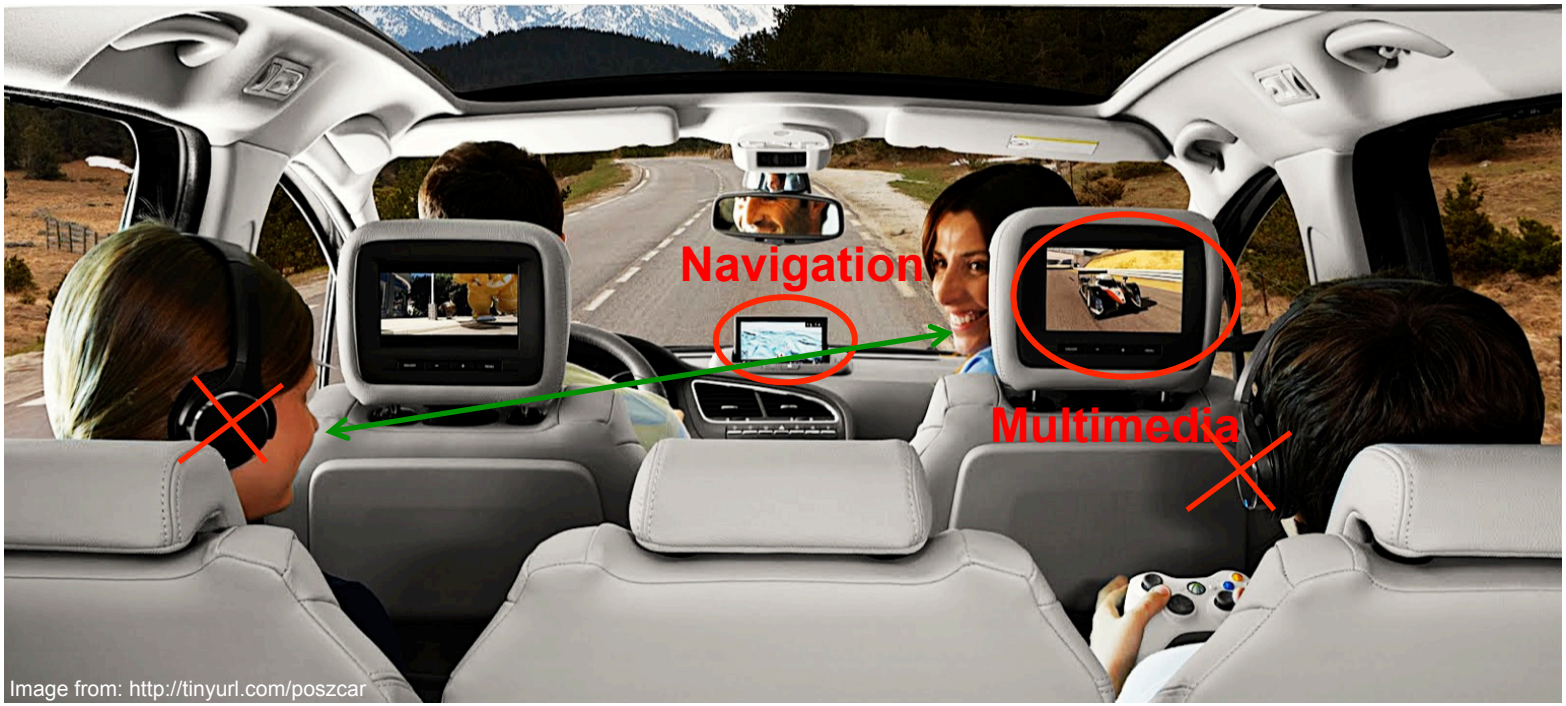
- **Competing audio streams in a shared acoustic space**



- **Ideally this could be delivered over loudspeakers**

Introduction

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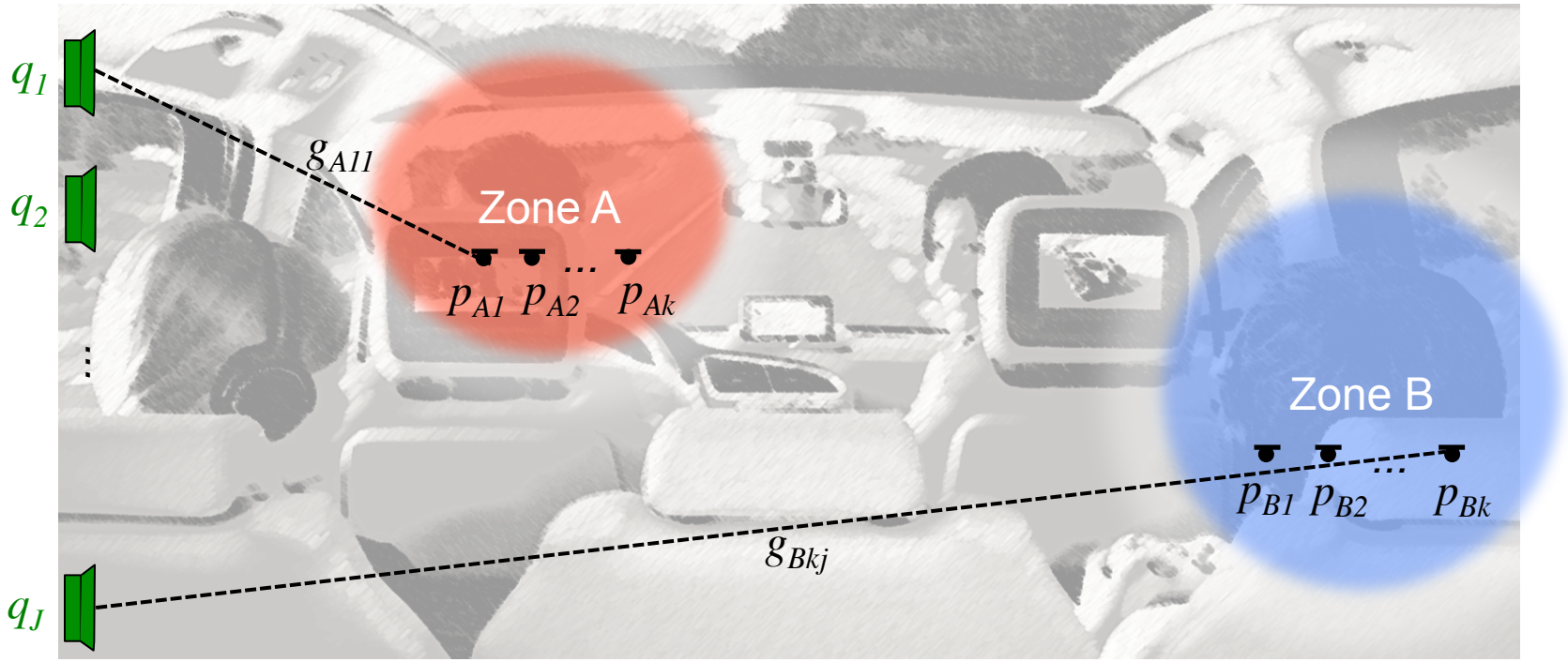
- **Competing audio streams in a shared acoustic space**



$$\mathbf{q} = \begin{bmatrix} q_1 & q_2 & \cdots & q_j \end{bmatrix}^T \quad \mathbf{G}_A = \begin{pmatrix} g_{A11} & g_{A12} & \cdots & g_{A1j} \\ g_{A21} & g_{A22} & \cdots & g_{A2j} \\ \vdots & \vdots & \ddots & \vdots \\ g_{Ak1} & g_{Ak2} & \cdots & g_{Akj} \end{pmatrix}$$

$$\mathbf{p_A} = \begin{bmatrix} p_{A1} & p_{A2} & \cdots & p_{Ak} \end{bmatrix}^T = \mathbf{G}_A \mathbf{q}$$

$$\mathbf{p_B} = \begin{bmatrix} p_{B1} & p_{B2} & \cdots & p_{Bk} \end{bmatrix}^T = \mathbf{G}_B \mathbf{q}$$

$\mathbf{R_A} = \mathbf{G_A}^H \mathbf{G_A}$ $\quad \mathbf{R_B} = \mathbf{G_B}^H \mathbf{G_B}$

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Sound Field Control Methods

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Brightness Control (BC)

Choi and Kim (2002) ...

- **Maximise acoustic potential energy in the target zone**

Focus beam on target zone → Delay and sum beamforming

Acoustic Energy Difference Maximisation (AEDM)

Shin *et al.* (2010)

- **Maximise difference of acoustic potential energy between each zone**

Maximise cancellation in terms of energy → Inverse methods

Acoustic Contrast Control (ACC)

Choi and Kim (2002), Elliot and Jones (2006) ...

- **Maximise ratio of acoustic potential energy between each zone**

Specify exact desired sound field → Sound field synthesis

Sound Field Control Methods

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Brightness Control (BC)

Choi and Kim (2002) ...

$$\alpha_{\text{brightness}} = \frac{\varepsilon_A}{\varepsilon_{A\,\max}} = \frac{\mathbf{q}^H \mathbf{R}_A \mathbf{q}}{\lambda_A \mathbf{q}^H \mathbf{q}}$$

Acoustic Energy Difference Maximisation (AEDM)

Shin *et al.* (2010)

$$\alpha_{\text{diff}} = \frac{\varepsilon_A - a\varepsilon_B}{\eta} = \frac{\mathbf{q}^H (\mathbf{R}_A - a\mathbf{R}_B)\mathbf{q}}{\mathbf{q}^H \mathbf{q}}$$

Acoustic Contrast Control (ACC)

Choi and Kim (2002), Elliot and Jones (2006) ...

$$\alpha_{\text{contrast}} = \frac{\varepsilon_A}{\varepsilon_B} = \frac{\mathbf{q}^H \mathbf{R}_A \mathbf{q}}{\mathbf{q}^H \mathbf{R}_B \mathbf{q}}$$

λ_A **Max. eigenvalue of** $\mathbf{R}_A$

η **Control effort**

ε **Acoustic potential energy**

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Motivation for Optimisation

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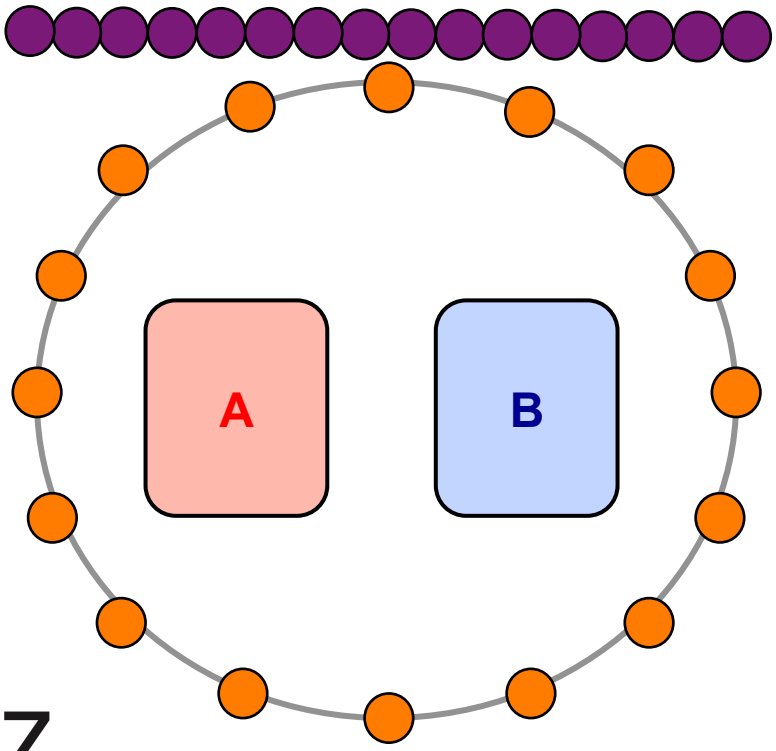
Where should we put the loudspeakers?!

- **Classical configurations usually adopted for sound zone realisations**
- **Line *e.g.* Chang *et al.* (2009a, 2009b), Park *et al.* (2010)**
- **Circle *e.g.* Shin *et al.* (2010), Jacobsen *et al.* (2011)**



Can we do better?
What if these positions are unavailable?

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Motivation for Optimisation

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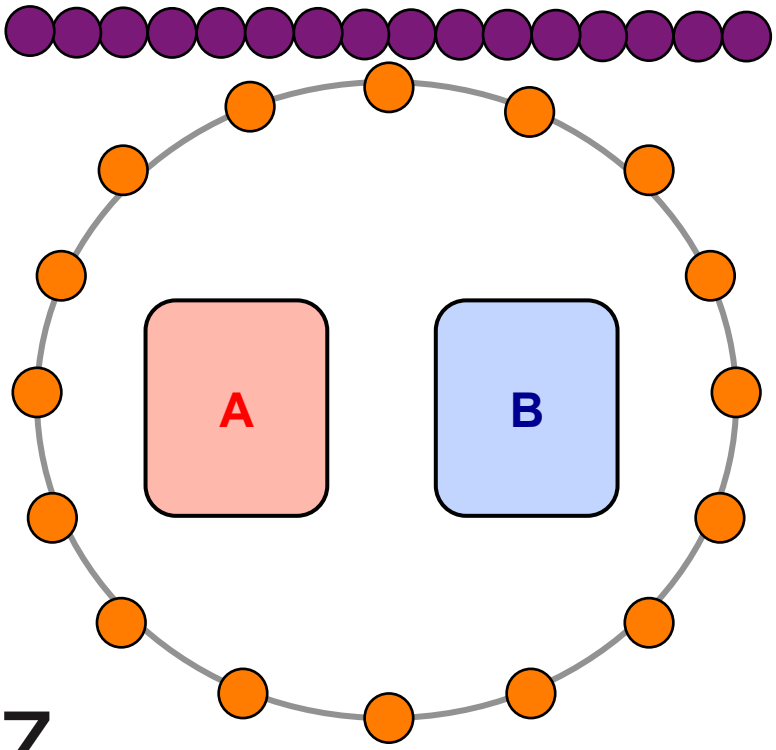
Where should we put the loudspeakers?!

Can we do better?
What if these positions are unavailable?



- **Use numerical optimisation to select positions**
- **Improve separation performance:**
  - Set up better conditioned problem
    Takeuchi and Nelson (2002),
    Bai *et al.* (2005)
  - Select the positions most appropriate for each zone
  - Vary selection over frequency
    Takeuchi and Nelson (2002)

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Loudspeaker Selection Procedure

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- ~~Alternatives: exhaustive search, genetic algorithm...~~
- "Plus *l* – take away *r*" (sequential forward-backward search)

  Devijver and Kittler (1982)
- Computationally simple
- Sequential forward search

$$Y(J_k + \xi_1) \geq Y(J_k + \xi_2) \geq \cdots \geq Y(J_k + \xi_{x-k})$$

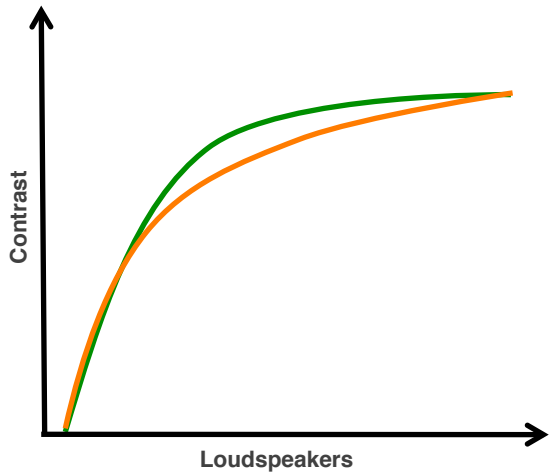
$$J_{k+1} = J_k + \xi_1$$

- Sequential backward search

$$Y(J_k - \xi_1) \geq Y(J_k - \xi_2) \geq \cdots \geq Y(J_k - \xi_{x-k})$$

$$J_{k+1} = J_k - \xi_1$$

- Parameters used: +2, -1



Cost Function

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- **Bai *et al.* (2005) proposed:**

$$Y = Performance + W \cdot Robustness$$

$$Y_{contrast} = \mathrm{SPL_A} - \max\{\mathrm{SPL_B}, 0\}$$

- **Atkins (2010) used matrix condition number as selection metric for WFS loudspeaker positions:**

$$\operatorname{argmin} \|\mathbf{W}\| \|\mathbf{W}^{-1}\|$$

- **Proposed log reciprocal matrix number penalty:**

$$Y_{condition} = 10 \log_{10} \left(\frac{1}{\|\mathbf{R}_B\|_1 \|\mathbf{R}_B^{-1}\|_1} \right)$$

- **Proposed cost function also includes term to constrain control effort:**

$$Y_{effort} = 10 \log_{10} \left(\frac{\mathbf{q}^H \mathbf{q}}{q_{ref}^2} \right)$$

$$Y = w_1 \cdot Y_{contrast} + w_2 \cdot Y_{condition} + w_3 \cdot Y_{effort}$$

Results – Anechoic Simulations

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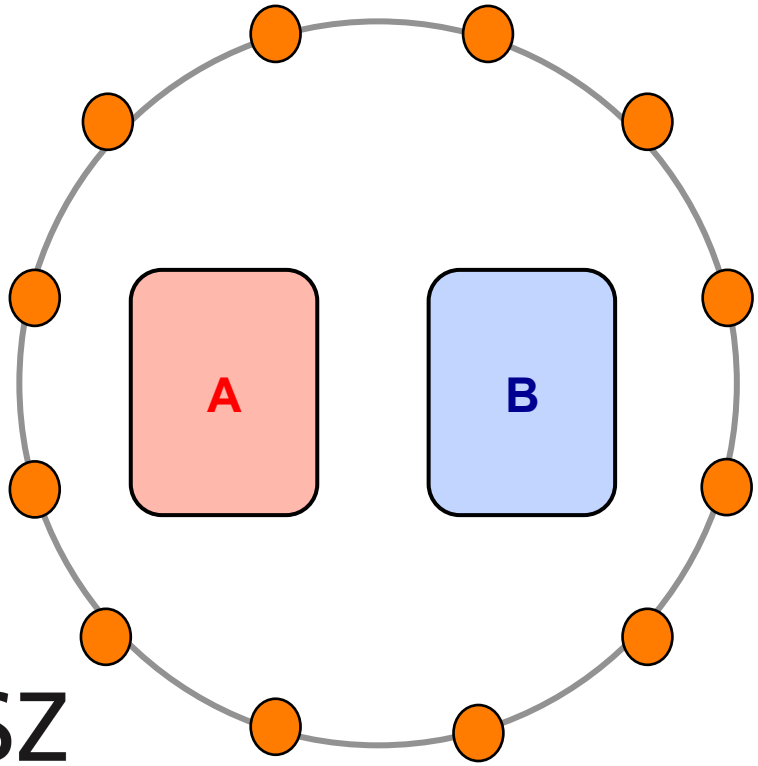
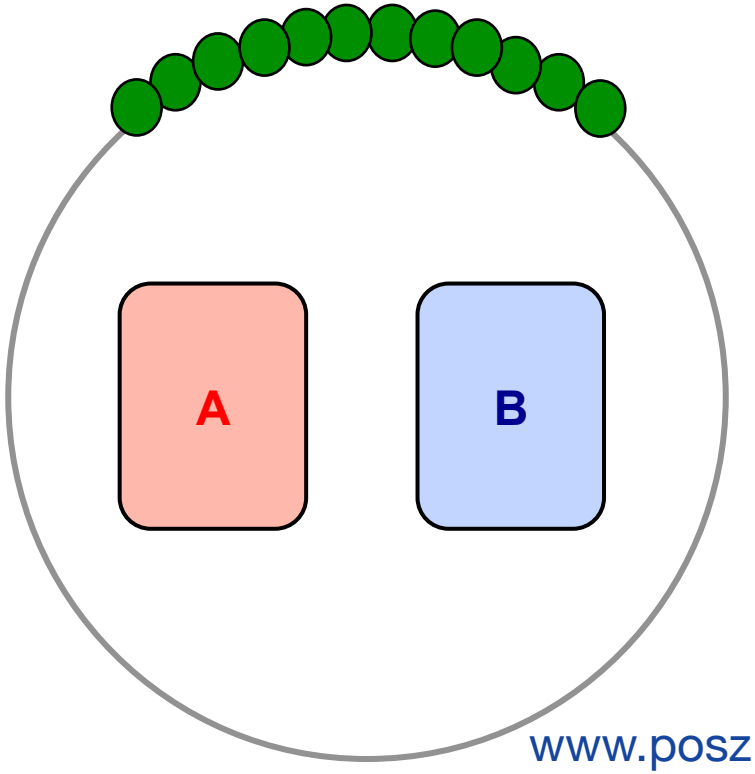
- **Demonstrate value of cost function elements**
- **Choose array of 12 loudspeakers from 98 candidate positions on a circle (forward search)**
- **'Classical' alternatives:**

Circular array



Arc array



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Results – Anechoic Simulations

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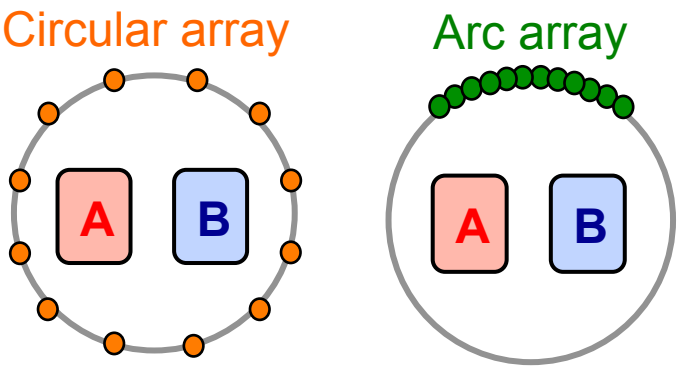
- **Demonstrate value of cost function elements**
- **Choose array of 12 loudspeakers from 98 candidate positions on a circle (forward search)**
- **'Classical' alternatives:**
  - Circle element spacing 77.5cm
  - Arc element spacing 9.6cm



- **Simulation conditions:**
  - Free-field anechoic room
  - Perfect monopole sources and microphones
  - Radius of circle – 1.5m
  - 2 circular zones – 30cm diameter
  - 7cm sound field sampling in zones
  - Spatially mismatched microphones for weight calculation/predictions
  - Simulations conducted in Matlab

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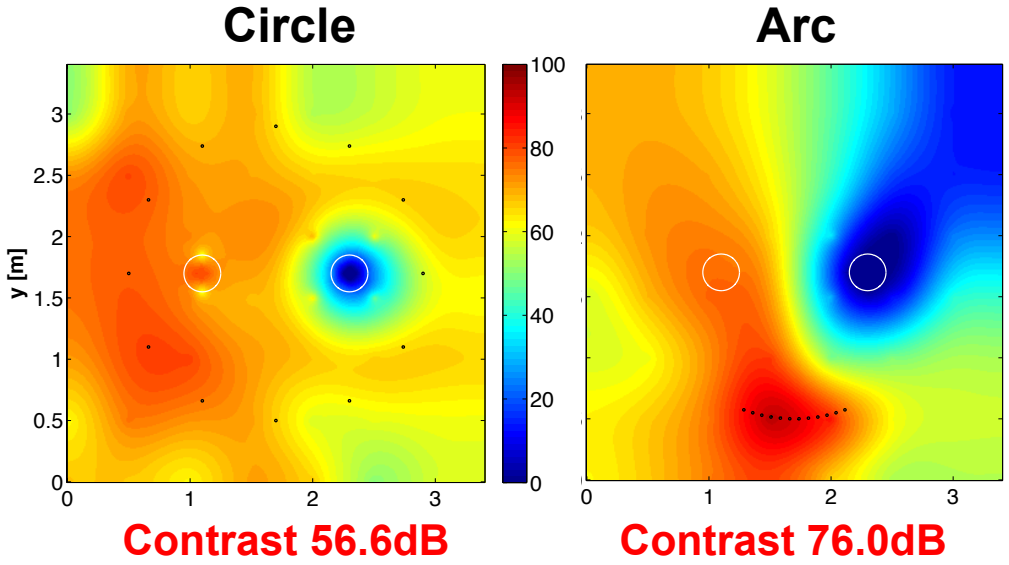
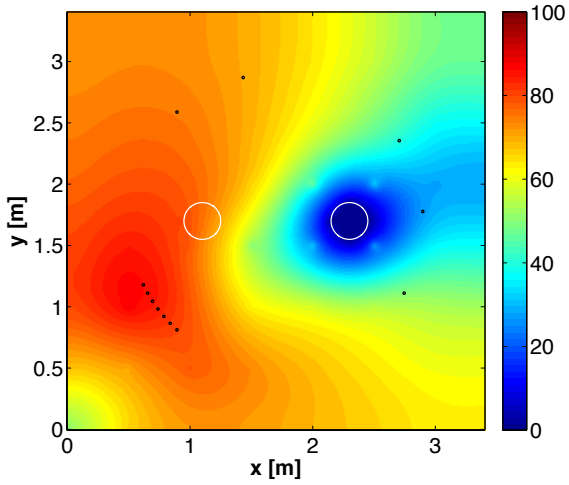
Results – Anechoic Simulations (1kHz)



- **Example based on acoustic contrast control**

$$w_1 = 1; w_2 = 0; w_3 = 0$$



Results – Anechoic Simulations (1kHz)

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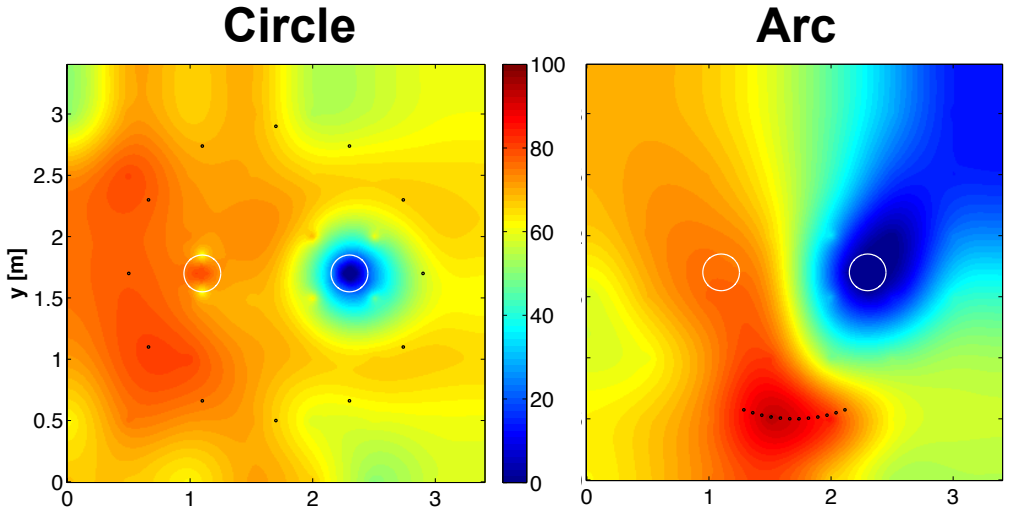
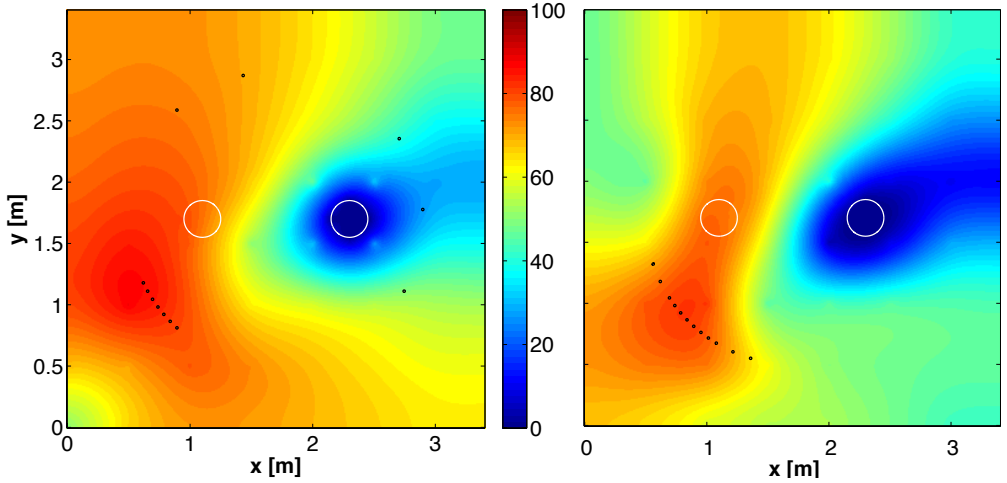


Contrast 56.6dB

Contrast 76.0dB

$w_1 = 1; w_2 = 0; w_3 = 0$

$w_1 = 1; w_2 = 0; w_3 = 1$



Contrast 76.0dB

Contrast 76.0dB

- Example based on acoustic contrast control

CONTRAST PERFORMANCE:

- Selected sets perform better than circle
- Selected sets perform equivalently with arc

CONTROL EFFORT:

- Control effort constraint improves effort and ‘spill’ against all other cases
- General SPL level indicative of degeneration due to reflections

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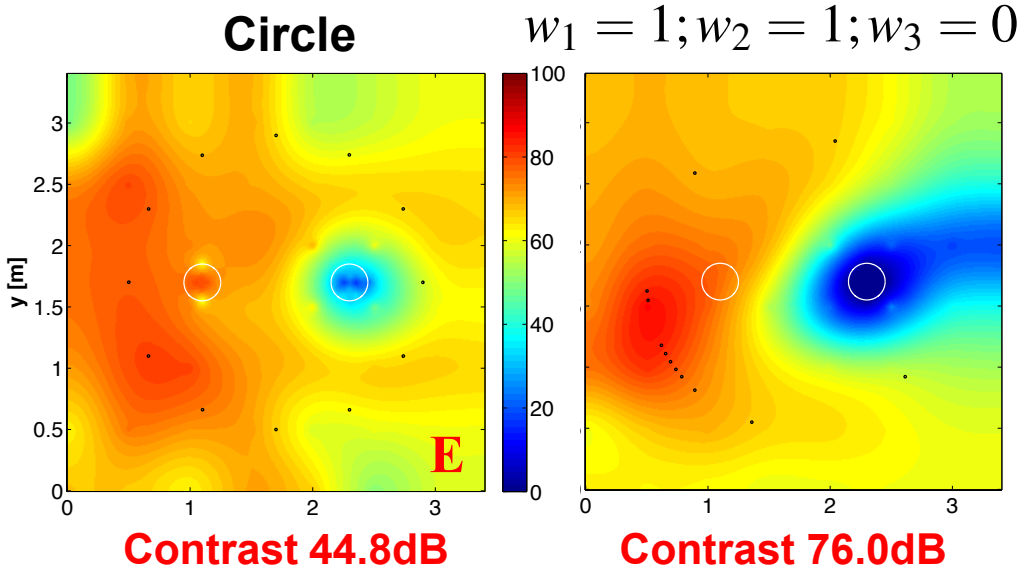
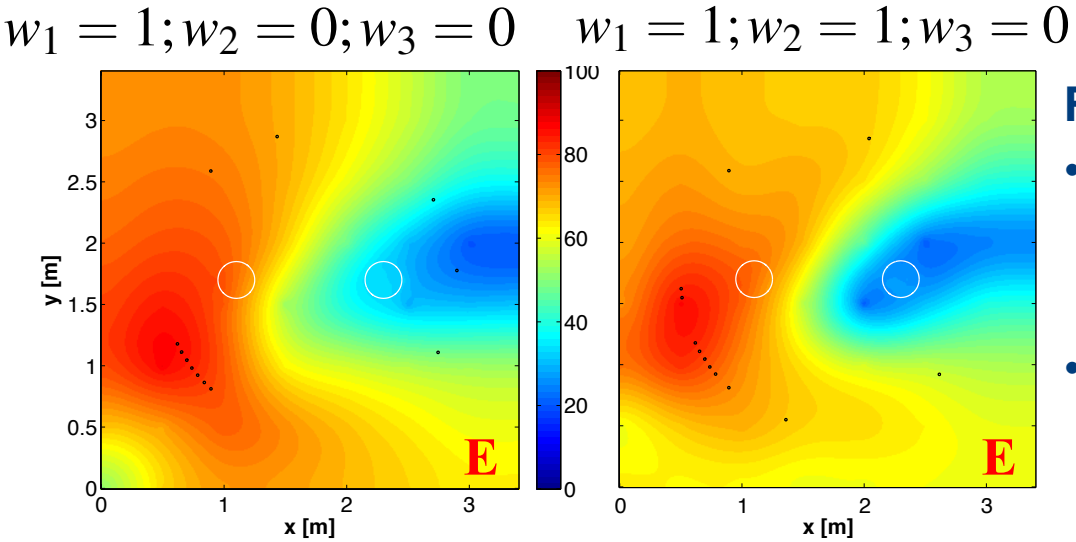
Results – Anechoic Simulations (1kHz)





- Example based on acoustic contrast control

MATRIX CONDITION:

- Optimal set produces equivalent contrast to previous cases

ROBUSTNESS:

- Random loudspeaker positioning error introduced

$$E \in (-1mm, 1mm]$$

- Produces best contrast case under error conditions

Results – Anechoic Simulations

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- **Anechoic simulations at 1kHz for alternative control methods**

		Circle	Arc	Optimal $w_1=1, w_2=0, w_3=1$
BC	Contrast (dB)	16.2	18.1	**26.7**
	Effort (dB)	-1.4	**-3.6**	-1.6
AEDM	Contrast (dB)	53.3	71.8	**76.0**
	Effort (dB)	-0.7	-3.0	**-3.3**
ACC	Contrast (dB)	56.6	**76.0**	**76.0**
	Effort (dB)	-0.4	-2.4	**-5.9**

- **Contrast improved by selection procedure**
- **Optimise cost function weightings to improve effort for brightness control**
- **Effort ref. – single monopole closest to zone A producing same SPL**

Motivation for Optimisation

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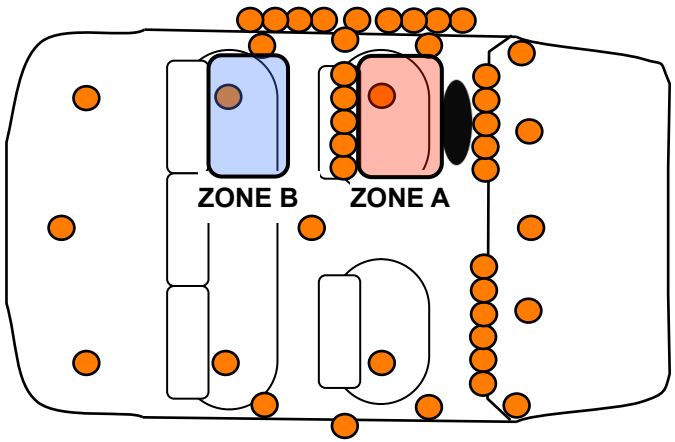
Where should I put the loudspeakers?!

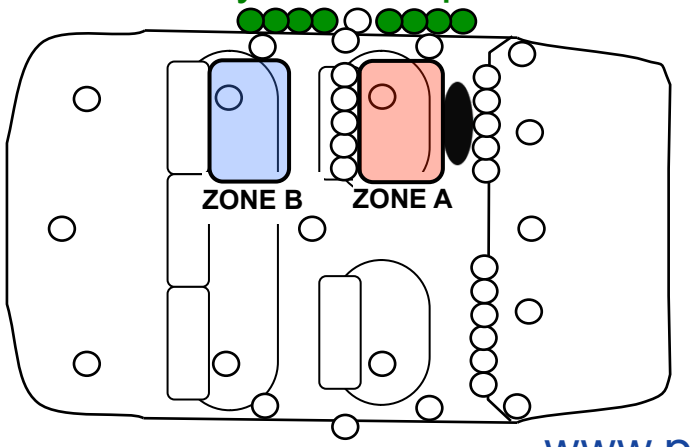
- **Practical problem in automotive environment**
  - Limitations on loudspeaker placement
  - Conventional arrays inappropriate
  - Errors exaggerated due to poor conditioning and measurement noise
  - Require a configuration for each zone

- **Comparison cases:**

All available loudspeakers



Line array of loudspeakers



Motivation for Optimisation

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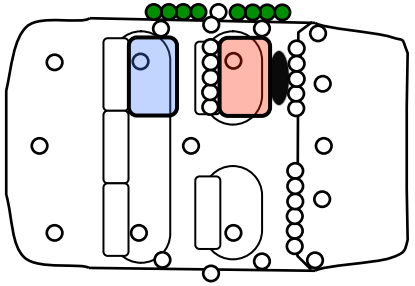
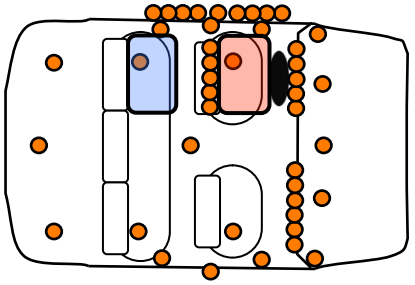
Where should I put the loudspeakers?!

- **Experimental setup:**
  - Backward search
  - TF measured using MLS
  - Candidate set: 38 midrange drivers
  - 40x40cm square zones, 7cm microphone spacing
  - Predictions generated by convolution in Matlab





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Results – Automotive Simulations (1kHz)

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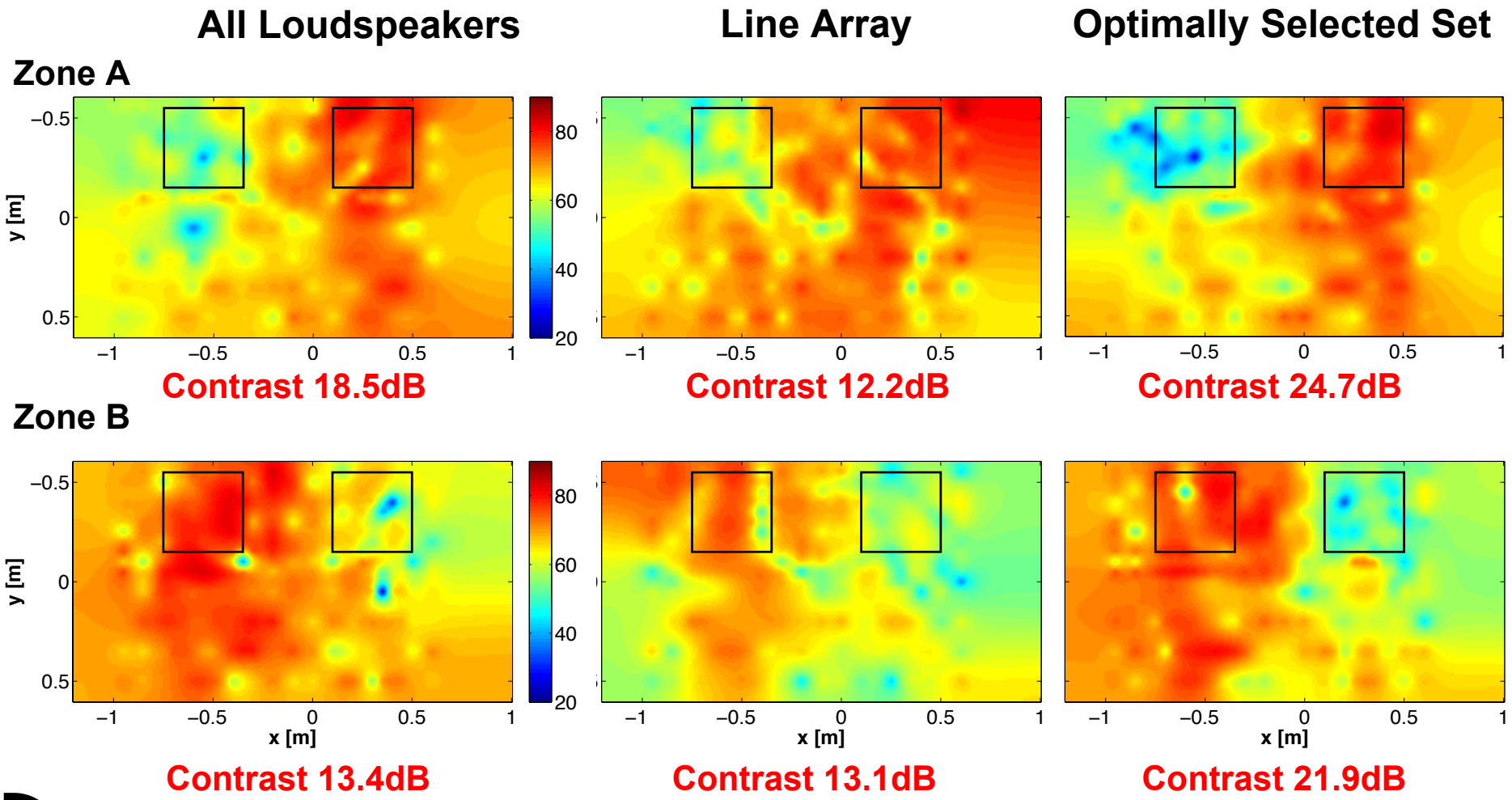

- **Optimally selected set outperforms alternative configurations**

Results – Automotive Simulations

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- **Results at 1kHz for alternative control methods (Target Zone A)**

		All	Line	Optimal w_1=10,w_2=1,w_3=0.5
BC	Contrast (dB)	8.6	7.6	**14.3**
	Effort (dB)	**-4.9**	3.1	-3.3
AEDM	Contrast (dB)	19.0	8.9	**24.2**
	Effort (dB)	**4.8**	19.1	6.2
ACC	Contrast (dB)	18.5	12.2	**24.7**
	Effort (dB)	6.2	11.4	**4.5**

- **Tentatively selected cost function weightings**
- **Contrast improved by selection procedure**
- **Cost function needs further development for effort performance**
- **Effort ref. – single driver closest to zone A producing same SPL**

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Summary

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- Investigated issue of loudspeaker placement for creation of personal sound zones using BC, AEDM and ACC
- Numerical optimisation is necessary to choose ‘best’ set of loudspeakers for practical realisations of sound zones
- Cost function incorporated performance, robustness and effort measures
- Anechoic simulations demonstrated equivalent contrast and robustness improvement
- Control effort was improved in some cases
- Practical results in a real car show improvement in contrast against benchmark cases

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